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Exploratory Visual Analysis for Animal Movement Ecology

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Abstract

Movement ecologists study animals' movement to help understand their behaviours and interactions with each other and the environment. Data from GPS loggers are increasingly important for this. These data need to be processed, segmented and summarised for further visual and statistical analysis, often using predefined parameters. Usually, this process is separate from the subsequent visual and statistical analysis, making it difficult for these results to inform the data processing and to help set appropriate scale and thresholds parameters. This paper explores the use of highly interactive visual analytics techniques to close the gap between processing raw data and exploratory visual analysis. Working closely with animal movement ecologists, we produced requirements to enable data characteristics to be determined, initial research questions to be investigated, and the suitability of data for further analysis to be assessed. We design visual encodings and interactions to meet these requirements and provide software that implements them. We demonstrate these techniques with indicative research questions for a number of bird species, provide software, and discuss wider implications for animal movement ecology.

Categories and Subject Descriptors (according to ACM CCS): H.5.2 [Information Systems]: Information Interfaces and Presentation—User Interfaces

1. Introduction

Animal tracking is increasingly important for studying animal behaviour and their interactions with each other and the environment [Nat08, KCW*11]. Sampled space-time data are often supplemented with temperature, accelerometer and other biometric data [WSL08, SBBvL*12]. These can help investigate research questions such as how individuals interact, the degree of diversity in behaviour between individuals, foraging strategy and migratory route fidelity between different years. Using data to answer such research questions requires them to be processed, segmented and summarised in different ways, producing derived data. For example, investigating differences in foraging behaviour amongst individuals requires some way of *quantifying behaviour* from sampled GPS points at appropriate spatial and temporal scales and then comparing these amongst individuals grouped in various ways. It may be that behaviour differs only at *particular times of year*, in *particular places* [KKL*12, OSFM10] or *particular groups of individuals*. There are many methods – ranging from manual to automatic techniques – for quantifying such behaviour [KS14, Sum14] and outputting derived data for visual and/or statistical analysis. Such methods require various parameter values (e.g. distance thresholds), data grouping and spatial & temporal scales to be defined. These should be informed by the characteristics of the data and topic of analysis and usually benefit from iterative process to identify appropriate parameters.

The *problem* that our workshops helped identify, is that data are derived *quite early on in the analytical process*, after which it is difficult to go back to. As such, *exploratory potential* of the original is lost. We therefore *identified a need* to facilitate exploratory analysis on relatively *unprocessed data*. Worked closely with a group of movement ecologists, we identify, design, implement and apply visual encodings and interactions from cartography, information visualisation and visual analytics to movement ecology. We want to use these methods in *initial phases of analysis* to help understand *how* and *how well* the data represent the phenomena of interest and how they might need to be transformed to answer various research questions. For example, measurement and sampling features [MSJ11] – noise, gaps, irregular sampling, biases and other complexities – affect the way in which data can be used.

Our *contributions* are to: *(a)* identify requirements for exploratory visual analysis for the *initial stages* of movement ecology analysis; *(b)* identify, design and implement visual encodings and highly interactive techniques from cartography, information visualisation and visual analytics; and *(c)* demonstrate their use in the context of bird movement ecology. Our work helps improve the use of animal movement data by making them more accessible, easier to discuss with others, easier to assess their suitability, speeding up the explorative-inferential analysis cycle, helping identify suitable subsets for subsequent analysis, and helping inform threshold and parameter selection. Software that implements this work with a video demonstrating its use are available from `http://gicentre.org/birdGPS/`.

2. Context and requirements

This work arose from the first author's research visit to the second author's animal ecology research group in 2011. The purpose of the trip was identify gaps in the animal ecologists' research that might benefit from interactive visualisation. Our user-centred process has already been reported [Sli11, SD12], but we summarise some parts here to provide details of the participants and how this research gap was identified. First iterations of the software took place within the research visit using rapid prototyping and feedback cycles [Sli11, SD12]. Work has continued since then, influenced by subsequent workshops (see acknowledgments) and continued use by the original animal ecology group as new data come in. The work reported here as the result of a long-term perspective.

2.1. Initial workshops from the research visit

The participants were four animal movement ecology scientists (including an author) – quantitative scientists who study the ecology of sea birds using data from GPS loggers. They work with different bird species, so there are difference in some of their approaches.

Firstly, a *"visualisation awareness"* session exposed them to a range of applied interactive visualisation examples in contexts both similar and dissimilar to their own. Its purpose was to show a range of possibilities and to encourage thinking outside current practice. For example, the ability to instantly compute local statistics on selections made interactively had not previously been appreciated, and it led to ways in which this technique could be used with their data to be conceived [SD12].

Current practice and its shortcomings were then identified. The ecologists commonly use R with existing libraries from the community, but liked the flexibility of being able to write their own scripts. Static visualisation already supports their work. Interactive visualisation was limited to a custom-built Google Earth-based tool that enabled them to look at the original data. They found the tool enormously helpful for confirmatory and validation tasks, particularly the aerial imagery. Limitations on the amount of data that could be loaded, a lack of control over temporal selection, and an inability to link to other interactive graphic types, were regarded as significant limitations. This was when the need for interactive visualisation to facilitate exploratory analysis of the *original unprocessed data* became apparent.

Initially, the discussion was based on validation/confirmatory tasks, centring on the shortcomings of the Google Earth-based tool. However, the extent to which visual exploration of the unprocessed data could start to address initial research questions was also discussed. To this end, we identified some *indicative tasks* representing the kinds research of questions one might try to investigate with the unprocessed data. The initial "visualisation awareness" workshop served as inspiration for this. These were *discussed and ranked* and were used to frame the evaluation (section 4):

- Can we infer an individual's behaviour along a journey?
- Which locations are frequently revisited, when and by whom?
- Which routes are frequently taken, when and by whom?
- When is there synchrony in behaviour?
- Where do individuals spend their time?

Some higher-level movement questions that these may help answer include the following. See section 4 for examples.

- How can we classify behaviour and segment journeys?
- What resources do individuals use (and where is further fieldwork needed)?
- What are individuals' home ranges and territories and do these change over time?
- Do individuals exhibit generalist or specialist behaviour?
- How do individuals move in groups?

2.2. Our aim

These initial workshops and subsequent work identified a need for the rapid exploration of the *original data* to: *(a)* help understand measurement and sampling characteristics of the data, to help assess suitability prior to data transformation; *(b)* to help identify thresholds, parameters and fieldwork necessary for further analysis; and *(c)* to explore initial research questions and help identify new ones. Studying *how* exploratory visual analysis can support animal movement ecologists explore newly-acquired data *prior* to cleaning, transforming and analysing, and the effect this has on the discipline is under-researched, yet important, particularly where vague ecological terminology such as 'stop-overs', 'fidelity' and 'home range' are used.

We also consider the following to be important roles for this work: *(d)* communicating interpretations to other audiences and *(e)* facilitating groups of domain experts – including those from complementary disciplines such as statistics, physics and computational geometry – to discuss how the data relate to the phenomena of interest and to help develop new methods to identify ecological artefacts and findings of interest. This is ongoing work.

2.3. Requirements

We created a set of requirements for interactive visualisation techniques to support animal movement ecologists, based on the outcomes of our original study, use of the resulting software and discussions at subsequent workshops.

R1: Provide access to original data

This direct response to the problem we are addressing is important for helping understand how the data represent the phenomena of interest. It reduces the chance of data being accidentally misinterpreted and of interesting characteristics being lost through transformation prior to their adequate understanding. As well as helping support the data interpretation, this can help provide input for subsequent analytical steps.

R2: Allow exploration space and time at different scales

Animal behaviour needs to be considered at a wide range of geographical and temporal scales to encompass foraging, feeding and breeding behaviour [SBvLP*12]. We distinguish between spatial and temporal *extent* and *granularity*, requiring techniques that facilitate exploration of both. Most interactive maps have zoom and pan functionality enabling cartographic scale to be interactively modified to explore data and background mapping/imagery at different extents and granularities. This is an important component of Shneiderman's Information Seeking Mantra [Shn96]. Although the same principles apply to time, such functionality is generally underdeveloped [AAD*10]. This was an inadequacy reflected in the workshop participants' criticisms of Google Earth's timeline. Since most statistics relating to spatial and temporal data are scale dependent [LP11] any reporting of these should be at the appropriate scale. We think there should be a dependency between cartographic (display) scale and reporting scale in visual interactive interfaces.

R3: Allow time, space and attribute perspectives to be related

Space, time and other attributes are intimately related for movement. Linking this so that these can be related at different scales is essential. Time has the additional complication that it can also be considered as cyclic, by year, week, day, hour [AAD*10]. Other attributes associated with data points are also important, particularly altitude and speed.

R4: Allow aggregation into "ecologically-meaningful" units

Many research questions relate to ecologically-meaningful units of analysis such as the "journey'. For example, one of the tasks identified in one of the initial workshops was to "infer a bird's behaviour along its track (journey)" and the journey view in the original prototype was considered useful and unique. Although we want to avoid imposing such interpretations on the data too early, we believe it is important to support the aggregation into ecologically-meaningful units where these have *already* been delineated and are of use.

R5: Provide rapid interaction with as few user interface interactions as possible

Visual analysis tools must facilitate but not disrupt the exploratory analysis process. Although quite an obvious requirement, it highlights the importance reducing barriers to visual exploration. Interactions must be immediately available with as few user interface interactions possible. In fact Beaudouin-Lafon [BL04] suggests "designing interaction, not interfaces" is an important component of achieving "fluidity" [EMJ*11] in interfaces. Drawing and interaction speeds are recommended to be at most a tenth of a second for drawing and animation and one second for interaction [CRM91].

R6: Provide continuous representations of discrete input data

The original data are sampled at discrete intervals, yet space and time are continuous, For analytical questions, simply presenting the original data points (*R1*) can be problematic, especially where irregularly sampled. Our solution is to interpolate continuous representation *on-the-fly* at a scale appropriate to the analyst's viewing of the data. Any required parameters need to be *interactively adjustable* with immediate feedback, because – as Laube and Purves [LP11] note – assumptions made whilst doing this will affect its output and perhaps its interpretation.

R7: Normalise statistics by time rather than frequency of sampled point.

Statistics based on frequencies of sampled points – for density estimates, histograms and tooltips – are problematic because points are usually irregularly sampled [MSJ11] in a manner that is independent of the phenomenon. This point was raised in the initial workshops. The usual approach is to resample data to fixed time intervals, but the disadvantage is loss of original data points (R1). Correcting on-the-fly and reporting time-based statistics is more satisfactory and helps address a common shortcoming that software often does not 'think temporally' even though analysts do [AAD*10].

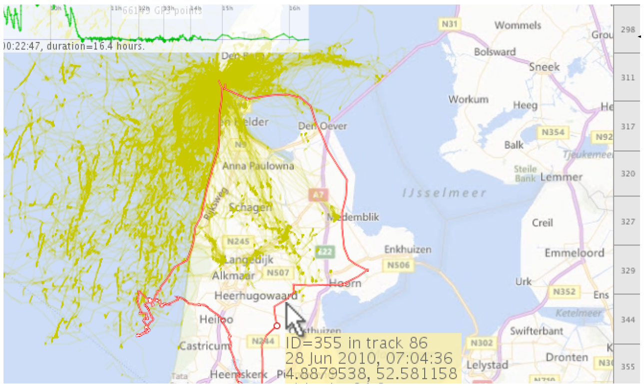

Figure 1: *Prototype software that implements the design.*

R8: Provide topographic maps and aerial imagery

Participants in the first workshop reported that background mapping was the most valuable aspect of their Google Earth based tool. Lautenschütz [Lau10] notes that these contextual geographical data are helpful for interpreting spatial data, particularly when the phenomenon is influenced by topography and landscape. Although an obvious requirement, it strongly influenced our original choice of implementation technology.

3. Visual encodings and interactions

Geographical depictions of data have a long history in cartography. Information Visualisation and Visual Analytics have taken interactive cartography to new heights. Many visual encoding and interaction designs exist for movement data [AA13]. BirdVis [FLF*11] is particularly relevant to our application area, using highly interactive visualisation to help understand bird populations. The focus towards the end of the analytical process, helping analysts understand species distribution models that combine crowd-sourced bird observations with habitat, vegetation and climatic data. Scheepens *et al* [SWvdW*11] support ship movement behaviour detection through composite multiscale density maps. Other work gets closer to the original data. Hurter *et al* [HTC09] study aircraft trajectories, supporting fast flexible spatial selection but only consider spatial aspects of the tracks. TaxiVis [FPV*13] provide means to visually build queries of millions of taxi trips and TrajectoryLenses [KTW*13] also suggests interactions for querying millions of trajectory based on origins, destinations and times. The Animal Ecology Explorer [SJM*11] gets closer to the original data with its focus on adding semantic content and Ware *et al* [WWF*14] get even closer, focussing on the 3D movement of individual whales as they

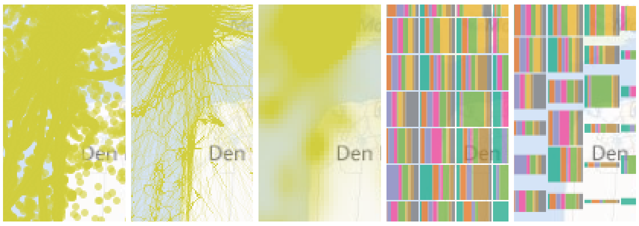

Figure 2: *Five mapping modes:* (a) *original points;* (b) *lines;* (c) *density estimation;* (d) *relative tile maps;* (e) *absolute tile maps, where b-e are coloured by duration spent there and (d-e) show relative duration of time spent by each individual.*

feed on the seafloor. This work draws on these advances and considers which techniques are relevant for supporting initial stages of analysis where initial questions are being asked of newly acquired data.

Our design is based on multiple coordinated views with brushing. Used in the original work, it was found to be extremely effective for relating spatial, temporal and attribute aspects of the data (*R3*). Each view contains the same data, but are arranged and formatted to represent different aspects. In our case, we have a geographical view, a linear timeline view, a cyclic timeline view and an individual view organised as shown in Fig. 1. Selecting data points in one view selects the corresponding data points in other views enabling these different aspects to be compared (*R3*). Software that implements the design is available (end of section 1).

3.1. Visual encodings

3.1.1. Map view

We have designed five types of map – points, lines, densities and two variants of spineplots – with base mapping or aerial imagery (*R8*). Each type of map is suitable to answering a different type of research question.

The **point map** in Fig. 2a shows the original data points directly (*R1*), but suffers from occlusion making it difficult to determine density. It is also sensitive to sampling rates (compare with the density surface in Fig. 2c). Points can be coloured by individual to help distinguish them (Fig. 3a), but these occlude each other making it hard to estimate diversity of individuals at locations. Since it is only possible to distinguish a small number of hues, we use a limited set (eight from ColorBrewer's 'DARK2' palette) and allocate these to individuals, reusing if necessary. If required, they can be distinguished through the tooltip or brushing.

All the other views use *aggregation* to compute densities to deal with the problem of occlusion. Aggregation is computed on the basis of screen pixels making them adaptive to the zoom-level, reflecting the spatial scale at which the data are being viewed (*R2*). They all report the *time they spent there* (*R7*), correctly compensating for irregularly temporally sampled as necessary on-the-fly. They also *interpolate linearly* between data points producing views that more closely match the original continuous phenomenon (*R6*). Interpolation only occurs between adjacent data points where the time difference is less than a threshold that is interactively adjustable giving

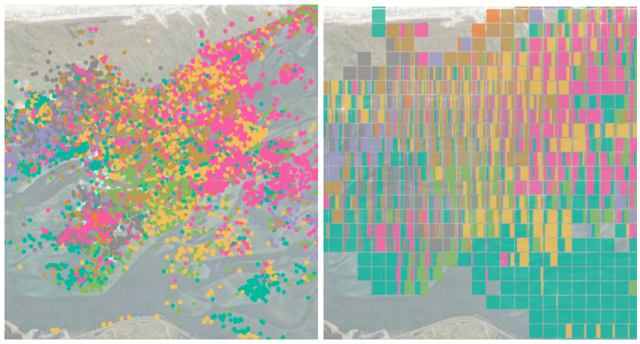

Figure 3: *Oystercatcher data on the mudflats: (a) Occluded point view, coloured by individual; (b) tile map showing the relative time of each individual in each grid square.*

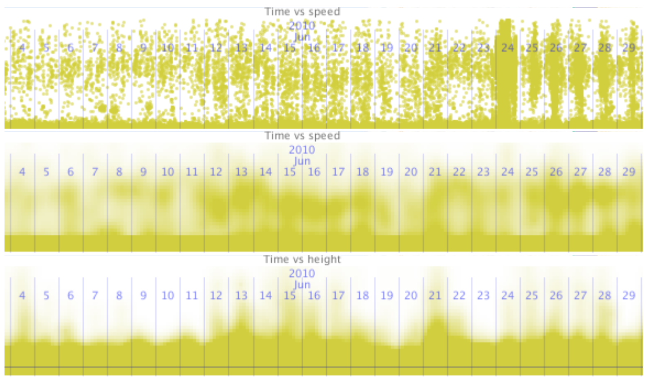

Figure 4: *Timeline modes:* (a) *original points as time (x-axis) against speed (y-axis);* (b) *density as time against speed, showing the time at which birds spent at different speeds over time (note the possible distinction between flying and non-flying speed);* (c) *density as time against altitude (y-axis), with birds spending more time at higher altitudes on certain days (e.g. 21st June).*

immediate results. As discussed, although this involves data transformation and inherent assumptions, we regard these as important for reflecting the original phenomenon. We do the computations on-the-fly and parameters that affect the transformation are interactively adjustable with immediate results. We use the simplest linear interpolation method between pairs of temporally adjacent points, whose time separation is less than an easily-adjustable threshold.

The **line map** in Fig. 2b clearly shows where the nest is and foraging trips in all directions. Comparison with the base map shows that many of these trips follow the coastline and Fig. 13 illustrates the time-based nature of the representation. The **density map** in Fig. 2c is similar, but uses a coarser spatial scale and a kernel to smooth the data to a local neighbourhood [WFD*99]. It linearly interpolates, does not show details of the tracks, but indicates where birds spend most of their time. The **'tile maps'** use stacked barcharts to aggregate to a coarse grid. By using individuals' allocated colours, they show *the proportion of time each individual spends at each location*. The second type of tile map sizes by total time spent. In Fig. 2e, the yellow bird spends more time than the other birds in

Figure 5: *The timeline is time plotted against individual (one per row). There is little variation in density, because data are time-normalised. The area highlighted the map is only visited by one individual shown in a red on the timeline. Zooming in on 24th June reveals that the individual visited the area twice on that day, once at 03:00 and once at 19:00.*

the top right area of the view. Fig. 3b illustrates how effective this method is for identifying usage of places by individuals and Fig. 16 compares male and female gull foraging areas.

3.1.2. Timeline vs other attribute view

Timelines are appropriate means to display time [Shn96]. Since the passage of time is one dimensional, we can usefully use two-dimensional screen-space to plot altitude, speed or other numerical attribute specified in the data time. In addition, there is also the option to use the *y*-axis to distinguish individual, as in Fig. 5. Due to the commonalities of time with space, similar principles apply and we offer points (Fig. 4), lines or densities (Figs. 4b & 4c), but our use of the *y*-axis is not compatible with the stacked barchart views. We have incorporated *two* timelines: a linear timeline (bottom left in Fig. 5) and a cyclic timeline for time of day (bottom right in Fig. 5) to meet part of *R3*.

3.1.3. Individual view

The stacked barchart at the top right of Fig. 6 represents the amount of time (*R7*) each of the eight individuals spent in the current map view. The highlighted portion of the lower two individuals represents the amount of time they spent in the highlighted (brushed) map area as reported by the tooltip. Where the point map uses colour to distinguish points or the tile map is used, it also acts as a legend as well as a statistical graphic [DWS10] (Fig. 6), depicting the colour allocated to each individual.

3.1.4. Journey view

There are obvious advantages to exploring bird movement data in ecologically meaningful units. Definitions are dependent on the species, the collected data, its sampling rate and the research questions being addressed. Here, we display journeys *if they have al-*

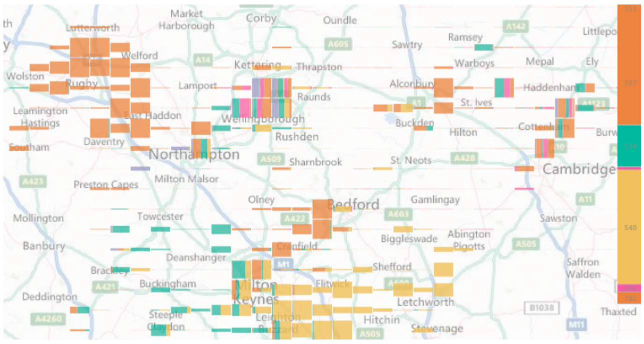

Figure 6: *Gulls' use of locations; the statistical legend on the right indicates the time spent in the current map view.*

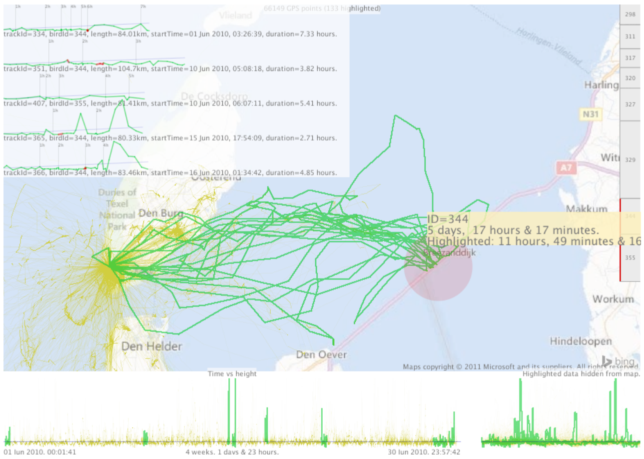

Figure 7: *Highlighted journeys on the map and timeline, with five of these journeys are shown (top) as distance from start on the (x-axis) against altitude (y-axis) with 1 hour isochrones (grey vertical lines).*

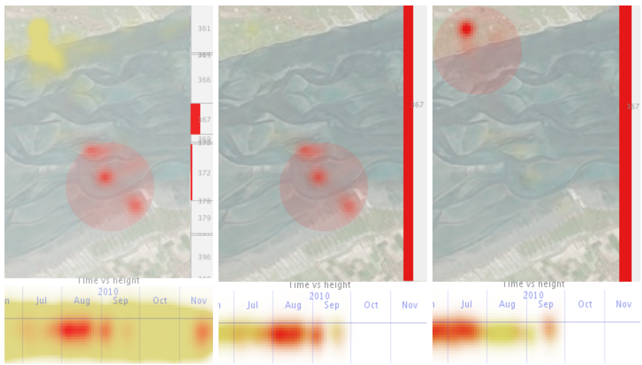

Figure 8: *Left: Oystercatchers tend to only be in the in brushed area in August, with #367 spending the highest proportion of time there than other birds. Middle:* Only #367 *shown, verifying it was indeed only there in August. Right: #367 was further North and on land earlier in the year.*

Figure 9: *Moving the mouse pointer over the density plot provides a tooltip whenever over an original data point (same dyke as in Fig. 7). If multiple data points are at that location, left/right clicking with cycle forward/backwards through these and any associated journey if one exists.*

ready been defined; i.e. if each data point that is part of a journey is marked with a journey ID in the input file. Gull trips used here are defined as *foraging trips* defined as those that start and end around the birds' nest site. Fig. 7 shows that two birds (see stacked barchart) visited the dyke fairly frequently during foraging trips at about the half-way point. The *x*-axis is *distance* from the start of the journey and the vertical lines are isochrones – birds spent more time at distances where these are closer together.

3.1.5. Access to details of original data points

Whichever display modes are being used for the map and timeline, the original data points are available (*R1*) and associated journey (if it exists). Fig. 9 shows a location on a dyke where one can cycle though all the points and associated journeys at the location.

3.1.6. Zoomable and pannable maps and timelines

Zooming on the map and timeline has two important roles. *Firstly*, it allows data to be visually resolved at different spatial and temporal scales; e.g. zooming into the timeline in Fig. 5 enables the time of day to be determined. Fig. 10 shows maps of the amount of time individuals spent at different locations at two spatial scales, where the large-scale structure can be interpreted using the aerial imagery option. The same principle applies for the timeline in Fig. 5, where zooming changes the temporal granularity. [LDH14] investigated various interactions for temporal zooming, but ours are closely aligned to those of the map. *Secondly* – and importantly for data exploration at different spatial and temporal scales (*R2*) – also controls the *scale* at which data are summarised (density plots, map-based stacked barcharts), brushing extents (section 3.1.7) and animation speed (section 3.1.9), allowing data to be explored at multiple scales, with background mapping (from a web map tiling service) and temporal tick-marks at the appropriate scale. Zooming and panning interactions are identical for both the map and timelines, are quick and simple (*R5*) requiring only simple motions, centred on the mouse cursor.

3.1.7. Simple & rapid brushing and persistence

Brushing [BC87] is an interactive means of selecting data in one view by 'brushing' a selection with the mouse. In multiple coordinated views, corresponding data points are highlighted in all views (e.g. [The02]), relate time, space and other aspects of data (*R3*). This is illustrated in Fig. 11. Of the places at which individuals spend time, the brushed area (in red) is mostly frequented by one

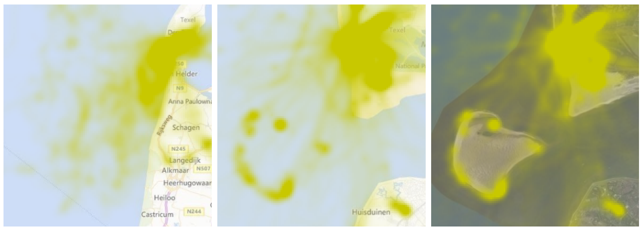

Figure 10: *Density plot scale computed according to zoom level. (Left) Zoomed to full extent – individuals spend most time around the nest; (middle) density at a large spatial scale, showing a loop structure; (right) Aerial imagery context helps to interpret the loop structure.*

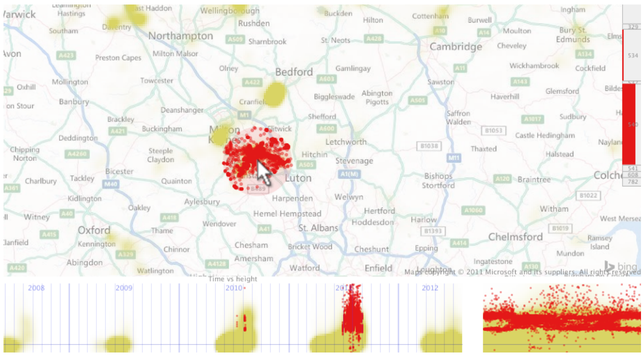

Figure 11: *Brushing an area on the map indicates the duration time of individuals' spent there as a proportion of the time they spent in the visible map area.*

individual in 2011, at most times of day. There appear to be two distinct altitudes of movement during the night, corresponding to two distinct journeys at that time of night at different altitudes. Fig. 11 illustrates that the brushed subset can be displayed in a *different mode* to the non-brushed data; in this case, density for the non-brushed subset and the original points for the rest.

We use 'transient' brushes [BC87] where the brushed area follows the mouse when SHIFT is down and persists when released. This behaviour makes the interaction in Fig. 5 possible: brushing an area on the map with the timeline zoomed out, identifying the times the area was visited at this coarse temporal scale and then zooming in to see temporal aspects at a higher temporal scale.

Brushing is performed at *appropriate spatial and temporal scales*. The size of the brush is based on a screen width which has the effect of brushing at an appropriate scale that for zoom level, thus the scale at which the analyst is using (*R2*). Pressing the LEFT and RIGHT keys during brushing (i.e. whilst SHIFT is down) on the map and timeline varies the width of the selection (distance or duration), along as a proportion of the screen width, thus an appropriate spatial and temporal radius increment/decrement.

3.1.8. Colour scaling

Transparency depicts time-spent on the map and timeline view, scaled between zero and an upper bound that can be interactively

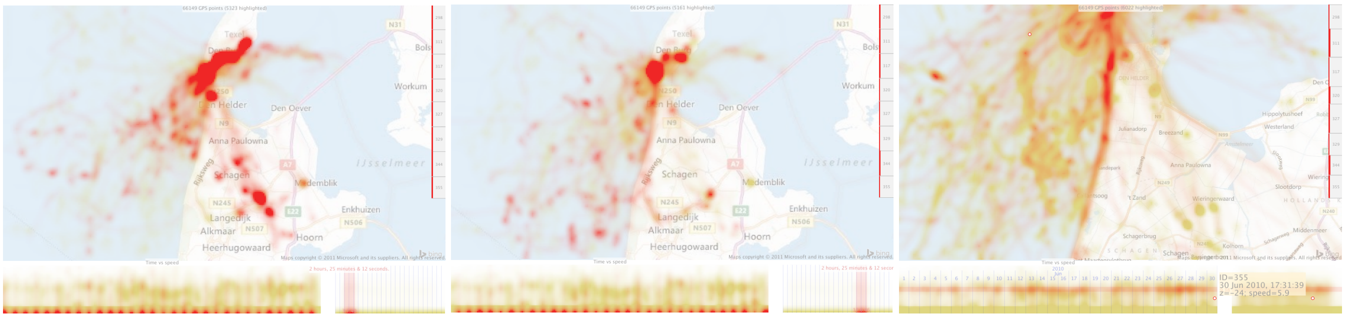

Figure 12: *Brushing modes. Left: Brushing early morning (03:00) on the cyclic timeline (right) to see the spatial distribution. Middle: Brushing the cyclic timeline (18:00) shows a different spatial pattern. Notice the repeated red highlighting on the timeline. Right: Brushing only high speeds of travel in attribute mode shows that travel along the coast is mainly at high travel speeds. The highlighted areas on the stacked barchart indicate that all these brushed subsets affect all individuals by a similar proportion of time to each other in the current field of view.*

adjusted using a linear mapping. It is important that colour scaling is *persistent* between zoomed/panned views for comparison, so colour rescaling as only changed by the user. A keystroke resets to the 95^{th} percentile (a good threshold) for the data and brushed portion independently) for the *current view* and the LEFT and RIGHT keys increase or decrease this value (by a tenth of its value). Colour scaling applies independently to the map and two timeline views.

3.1.9. Animation

When the timeline is brushed, it can be animated forwards in time at a speed *appropriate to the timeline zoom level*; thus zooming the timeline will adjust the speed of the animation appropriately (*R2*). Such animation is appealing because movement is depicted directly and it effective for presenting temporal trends but [RFF*08] show that is difficult to *identify* trends, except over very short timescales.

4. Validation and investigations

The original research visit and was followed up by some evaluation a couple of months later [SD12] with three of the original participants. Using the questions identified in the workshop (section 2.1), a new download of data was explored and this was used to provide answers to each of the questions. At the end, participants were asked to assess how well the interactive techniques provided by the software facilitated answering the research question. The questionnaire tried to separate *techniques* from *user-interface* as the software was still a prototype. Quantitative data was overwhelmingly positive, showed that they were able to use the software independently to carry out tasks it was designed to carry out. This was confirmed by screenshots that showed how the software was uses to answer to the questions. More useful, were the comments which have informed subsequent improvements. The research group continue to use this software to explore new data that come in.

We now provide examples of how the interactive techniques can be used for wider questions.

4.1. Classifying behaviour and segmenting journeys?

The map in Fig. 13 shows intriguing dark (indicating more time spent) 'hook-like' structures apparent on the sea but not on land.

Figure 13: *Intriguing 'hooks' of floating birds being moved by the tide [SBBCB11].*

Figure 14: *A lesser black-backed gull's day trip to Amsterdam exhibiting soaring and gliding behaviour.*

On further investigation (including determining their altitude) it was discovered that these are birds floating on the sea and being moved by tidal forces [SBBCB11], information that could be used in a segmentation or classification algorithm later. Where journeys have been specified, behaviours along the journey length can be explored and this may help further segment journeys. The journey view and ability to identify structure along it was considered one of the more unique and useful views provided by the original prototype. Fig. 14 indicates a journey to Amsterdam. The map-brushed area is highlighted in the timelines and the journey view (top), the latter view indicating that Amsterdam was about a third of the way into the journey. The closeness of the isochrones indicates speed and the gliding and soaring behaviour of the gull taking advantage of thermals around the urban area.

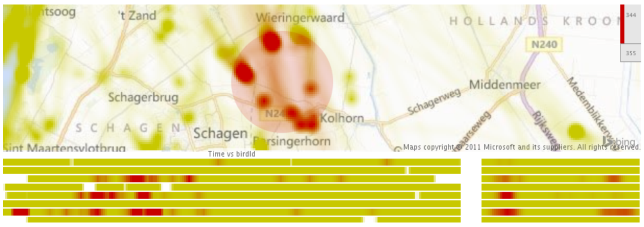

Figure 15: *Brushed area visited at 03:00 in Fig. 12 (left) is visited in the morning and evening, mainly by three gulls.*

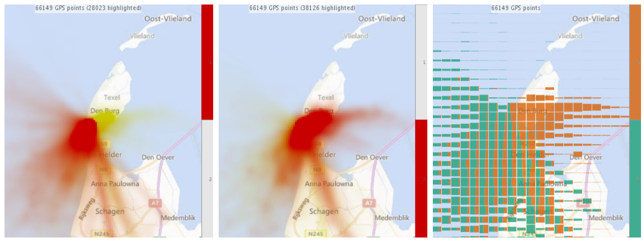

Figure 16: *Foraging ranges of male gulls (left) and females (middle) with proportions of time for each shown as a tile map (right).*

4.2. What resources do birds use (and where is further fieldwork needed)?

Sites visited frequently by one or more birds are likely to contain resources important to them, but we often do not know what they are. A recent project (`http://www.vogelhetuit.nl/`) is investigating where and when resources are available to lesser black-backed gulls. It is doing so by establishing where resources *might* be and then asking *members of the public to do fieldwork* to help identify locations to which fieldwork should be directed. Data are automatically downloaded from the tracking tags when they return to their nest. Using the software, members of the project identify 'interesting sites' – those regularly revisited, those that have particularly long visits and those that appear to be avoided. For example, Fig. 12 (left) illustrates that gulls spend time near Winkel. Brushing this area in Fig. 15 indicates that this area is only visited in the mornings and evening, mainly by three gulls and mainly in the first half of the month. Such behaviour suggests that this place is significant and fieldwork is needed to establish why.

4.3. Where are birds' home ranges and territories and do these change over time?

Two important concepts in animal ecology are the *home range* (the area used for an animal's daily activities and whose extent may indicate scarcity of resources) and the *territory* (area that an animal uses and defends). These can vary greatly by time, sometimes even week-by-week. Territory size can give clues about breeding strategies [EKBH92], but also dietary requirements and travel constraints related to a bird's breeding stage [BEHdV96]. Fig. 8 shows an example where during chick rearing in July, a bird spends most of its time near the nest on the salt marsh, whereas after fledging in August when food becomes more scarce, the individual spends most of its time on the mudflats where there is more food.

Research on lesser black-backed gulls has aimed to identify differences between male and female home ranges in order to feeding strategies, dietary requirements and the risk adversity of behaviour [WED*08]. Fig. 16 codes gulls by gender, indicating they have different foraging areas with females using more terrestrial habitat and a large portion of the Wadden Sea. We speculate that males' larger size gives them competitive advantage over females when foraging over the North Sea because of the efficiency of higher flight and greater chance of acquiring prey around fishing vessels, whereas females take advantage of shrimp fishing in the Wadden Sea and forage on land.

4.4. Generalist or specialist behaviour?

Individuals' locations and routes are strongly influenced by food availability, the energetic cost of movement, safety from predators and familiarity. For generalist species at a *population* level, the degree of *individual* specialisation and consistency of this strategy through time is interesting [Val65]. Gulls display a high degree of individual specialisation, as exemplified by the visits to the dyke in Fig. 7, however this behaviour is mixed with strategies that coincide more with gender (see section 4.3). In spite of these individual differences, route and site fidelity can be observed. Fig. 12 (right) indicates that coast is an important route at flying speeds. Such routes are energetically beneficial because the dune ridge leads to wind conditions in which the gulls can use soaring flight. An example of a location that is visited by multiple individuals is the outer-fringe of a sandbank near the breeding colony (see Fig. 10), at which gulls rest and probably socialise.

4.5. How do birds move in groups?

Homing pigeons and other flocking birds benefit from flying in groups, but the group dynamics of how collective decisions are made, which individuals contribute to these decisions and why, remain open questions. [FAN*13] investigated this by releasing homing pigeons where individuals had different homing experiences, studied the leadership hierarchies and found that experience did not significantly affect leadership hierarchies. Fig. 17 uses these data to demonstrate how timeline brushing can help visually investigate flocking and leadership and indicates how the flock splits into subflocks, that individuals stay close to each other in their subflock, but time-lags emerge between different subflocks. Detailed visual inspection of southeastern-most subflock (zoomed in Fig. 17) established that they remain seconds apart with one individual leading most of the time, occasionally being replaced by another.

4.6. Other applications

Although our context has been that of animal movement ecology, many of the techniques are applicable to other applications. Adaptations may need to be made for different data or question characteristics. For example, if the positional data were of varying precision (e.g. derived from mobile phone cell ID), visual representations of this uncertainty would be appropriate. An earlier version of the software was adapted to study human behaviour through data logged by their mobile phones [SBW13] with extra linked views for looking at phone communication between subjects of the study.

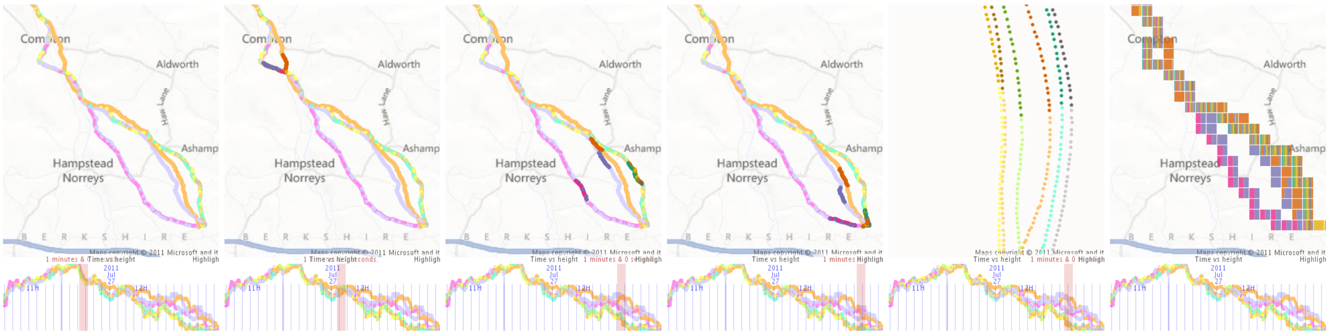

Figure 17: *Ten homing pigeons [FAN*13]. Group behaviour can be explored by colouring the dots by individual and brushing the timeline (top row). Brushed dots are highlighted in the darker colour and zooming in (bottom left) can help identify the structure of the group. The map-based spineplots (bottom right) summarises which pigeons took which routes.*

5. Discussion and Conclusions

The first contribution of this work *identifies a number of requirements* for interactive visual exploration techniques for supporting movement ecology in the early stages of analysis. This may be useful for designers of such systems. In order to help understand the way in which the data represents the phenomenon of interest and to not impose parameters that may lead to us miss important patterns, we keep the data is its original form, performing transformations on-the-fly in response to analysts' input. Of the requirements, four are worth highlighting. *Exploring space and time at different scales (R2)* allows different spatial scales of behaviour (migration versus flocking behaviour as in Fig. 17) to be studied. Although spatial scale is often supported well in such software, the same is often not true for time. *Rapid interaction with few user interface interactions (R5)* aims to facilitate exploratory analysis without disrupting the exploratory analysis process. Tools must strive to do this. Showing *space and time as continuous (R6)* is important because discrete data points are often irregularly sampled and are usually not significant in themselves for describing the continuous process of movement. Finally, movement ecologists are more interested in *temporal duration-based statistics (R7)* than number of data points, important particularly where data points are irregularly sampled.

The second is to *suggest and justify visual encodings and interactions to support this*. We suggest multiple coordinated views that are linked with brushing using ideas taken from cartography, information visualisation and visual analytics. We adapt these in some novel ways to meet our requirements including using time duration based graphics, tile maps that show time spent by multiple individuals, fluid zooming, panning and brushing that can be performed in space and time at different scales, on-the-fly. The design of this implementation has been described in this study and is implemented as a freely-available tool – see end of section 1.

The final contribution is to *demonstrate their use in the context of bird movement ecology*. Section 4 does this, demonstrating how the rationale of this work, requirements, visual encodings and interactions help investigate animal movement issues of importance.

Ongoing work includes incorporating other data sources such as wind (known to have a strong affect, particularly on migration), measurements from biometric sensors and observation data. We also consider these techniques to have important roles for communicating interpretations to different audiences and facilitating discussion amongst domain experts. We plan to investigate these in animal movement workshops over the next couple of years.

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